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Extreme Nonlinear Optics of High Intensity Laser Pulse Filamentation in Gases

Howard Milchberg
MARYLAND UNIV COLLEGE PARK

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Final Report

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Main 2015-2016 accomplishments:
* high sensitivity measurements of air absorption of energy from femtosecond filaments. Published
* absolute measurements of electronic, vibrational, and rotational nonlinear response in H2 and D2. Published.
*first measurement of nonlinear index in the mid-IR (low wavelength end). Published
*acceleration of electrons to 10 MeV energy using record low laser pulse energies. Published
*discovery of spatio-temporal optical vortices. Submitted.

15. SUBJECT TERMS
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Final Report

AFOSR grant FA95501310044 (2013-2016)

Extreme Nonlinear Optics of High Intensity Laser Pulse Filamentation in Gases

Principal Investigator: H.M. Milchberg

Summary of work performed under this grant

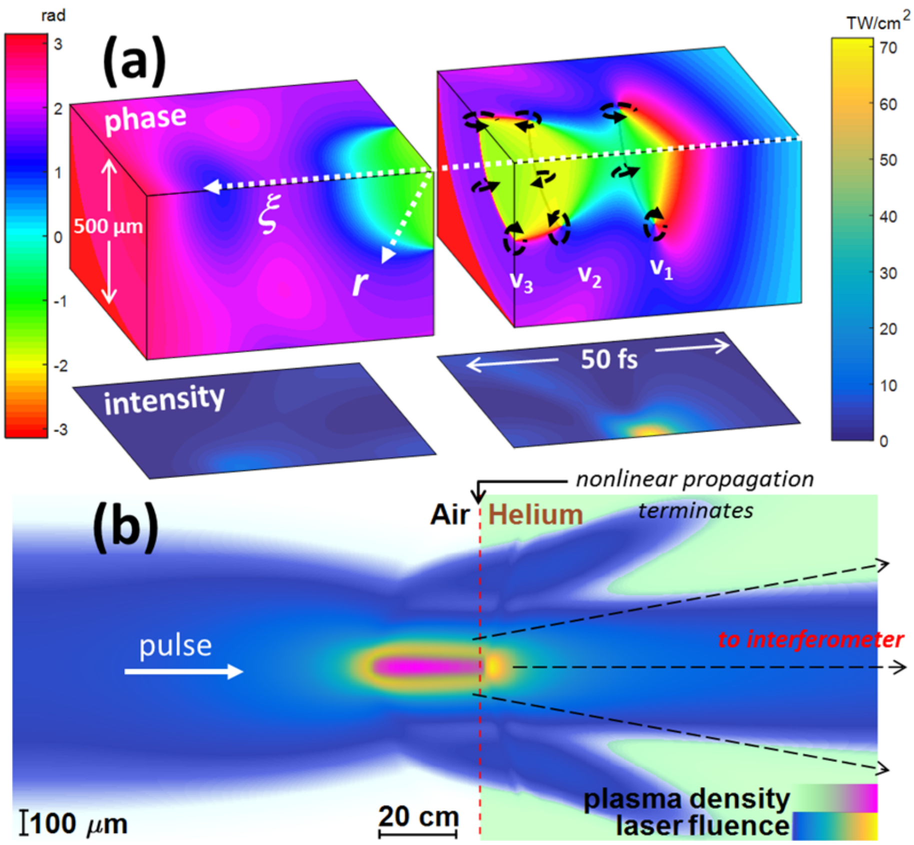
The work performed under this grant explored nonlinear pulse self-collapse and filamentation, the underlying physics governing the process, and applications. In work just preceding the beginning of this grant, we made the first measurements of absolute axially resolved electron density in filaments. In addition, in twenty years of experiments in air filamentation by other groups, there was no detailed distinction made between the instantaneous and rotational nonlinearity of N_2 and O_2, the molecules of obvious interest for air propagation of high intensity laser pulses. Prior groups, motivated by Mysyrowicz *et al*., assumed that the contributions were 1:1. We established, in work supported under this grant, that in most filament experiments with pulse durations greater than ~100fs, the dominant nonlinearity was rotational. We proceeded to measure both the instantaneous and rotational contributions absolutely, finding that the relative contributions are pulsewidth dependent, with the instantaneous response dominating at <30 fs and rotational dominating at >120 fs, and with the vibrational response much weaker than either.

We also determined, as a follow-on to the contentious so-called high order Kerr effect (HOKE) debate, that the instantaneous nonlinear response scaled as the square of the laser field all the way to the ionization threshold, ruling out the higher order Kerr effect and greatly informing the development of propagation models. The ultrafast time resolution of our diagnostics (spectral interferometry) used for these measurements enabled absolute measurements of the instantaneous and rovibrational coefficients in the fastest rotating molecules H_2 and D_2, which can serve as a benchmark for theory of high field molecule interactions.

One of the persistent unexplained aspects of our spectral interferometry experiments of absolute ionization rates was a lower than expected yield. Ultimately this was traced to a lower than anticipated target gas density owing to gas heating by the kHz pump pulse. This led to the realization that air waveguides could be generated with gas heating by filaments (and also by a sequence of non-ionizing pulses separated by the quantum molecular revival of nitrogen, which could potentially heat air even more than via plasma generation). This led to a new research area, unanticipated in the original AFOSR proposal, of air refractive modification by nonlinear absorption of femtosecond pulses. Femtosecond laser-driven air hydrodynamics evolved at short times in the acoustic regime and at later times in the thermal diffusion regime. Air waveguiding of high power pulses was demonstrated in both regimes.

In order to understand the collapse and filamentary propagation of high order modes, which was an important component of our air waveguide generation, we undertook experiments to measure the intensity and phase of filaments in mid-flight. This has led to a new result, the discovery of spatio-temporal optical vortices (STOVs). STOVs not only explain the continued phase coherence of multimode beams after collapse, but we believe they provide a unifying principle for all self-focusing and propagation phenomena. We believe that the study of STOVs will develop into a sub-field in its own right. The figure below shows (a) a propagation simulation of STOV generation and (b) the scheme used to measure the intensity and phase of the filament mid-flight. For more details, see **arXiv:1604.01751** .

On a low repetition rate laser system (10Hz) we demonstrated relativistic collapse and filamentation and electron acceleration using high density H_2 gas jets and as little as 10 mJ laser energy. We are porting these experiments to new laser system just installed in the lab, which has a higher rep. rate of 1 kHz , 5x greater pulse-to-pulse energy stability than the 10 Hz system, and ~3.5x more energy pulse than the kHz system it replaces. This new laser will extend the measurements of the prior grant cycle to the relativistic domain, with a low signal to noise ratio for accurate absolute measurements.



(a) Phase and intensity projections of simulated pulse, in local coordinates, showing STOV generation. (b) Simulation of an air filament crossing the air-helium boundary for the conditions of (a), showing the beam fluence and plasma density. Nonlinear propagation terminates as the beam transitions from air to helium, whereupon the beam and a reference pulse are directed to an interferometer.

In filament-based THz generation experiments using two-colour (400nm and 80nm) drive pulses in the atmosphere, the 2 TW 10 Hz laser in Milchberg's lab was used in several geometries—elongated axial filamentation and cylindrical lens focusing to generate two-colour filament bundles lying in a sheet--- to regenerate record high THz fields up to 21 MV/cm.

Patent applications made under support of this grant:

1. *Waveguides, And Systems And Methods For Forming And Using Such Waveguides*, US provisional patent application (air waveguides)

2. *Laser-Driven High Repetition Rate Source of Ultrashort Relativistic Electron Bunches*, US provisional patent application (1 kHz, millijoule laser accelerator).

Publications 2013-2016

1. *Effect of two-beam coupling in strong-field optical pump-probe experiments*
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Extreme Nonlinear Optics of High Intensity Laser Pulse Filamentation in Gases

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Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Howard Milchberg

Program Manager
The AFOSR Program Manager currently assigned to the award

Enrique Parra

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Reporting Period End Date

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Abstract

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Extensions granted or milestones slipped, if any:

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Research Objectives

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